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Interelectrode space effect on power dissipation and silicon oxide thin film growth from TEOS/O_2 discharges

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Abstract The effect of the electrode gap on the electrical properties of TEOS/O_2 discharges and on the growth rate of silicon oxide thin film was investigated. The experiments were performed using two excitation frequencies (13.56 MHz and 27.12 MHz) and at conditions that lead to deposition of films with a high inorganic character. Higher electrode gaps were always followed by an increase of the power consumption and the deposition rate. An additional enhancement was found with an increase of frequency from 13.56 to 27.12 MHz, indicating that a combination of high electrode gaps and frequencies are necessary for the fast deposition of inorganic SiO_2 thin films from TEOS/O_2 discharges.

1. Introduction

The deposition of SiO_2 thin films using tetraethoxysilane is a promising method in very large scale integration (VLSI) technology for interlayers, gate oxide and passivation layers due to their low defect density and the superior conformal step coverage [1]. Among the techniques used for the deposition of SiO_2 thin films, Plasma Enhanced Chemical Vapour Deposition (PECVD) appears the significant advantage of the deposition at very low temperatures (< 400 ^{o}C) [2–5]. In PECVD, the plasma is used as an aid to chemically decompose the organosilicon (TEOS) precursor and as a source of active species involved in the film growth.

The major problem of the SiO_2 thin film deposition from TEOS/O_2 electrical discharges is that the complete removal of carbon and hydrogen that already exist in the gas precursor is a difficult procedure that requires a careful optimization of the whole plasma parameters. This removal is also very essential for the application of these films on microelectronic devices as the presence of either carbon or hydrogen even in very low concentration reduce significantly the device efficiency [6].

Previous research on the nature of SiO_2 thin films produced with TEOS-based plasmas have shown that the RF power and the concentration of the oxidant in the gas mixture play the most important role for the achievement of highly inorganic thin films [7, 8]. From the above mentioned parameters the effect of the RF power is not very well understood yet, mainly because of the insufficient way of calculation of the real power dissipated in the discharge and the insufficient coupling of the RF generator with the plasma [9]. In most of the cases, the increase of RF generator power is not followed by an analogous increase of the power dissipated in the plasma because of the changes in the plasma phase impedance and also of the changes of the power dissipated in the external circuit. These changes significantly limit the amount of power that is transferred to the plasma and affect also the inorganic

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character of the deposited films if we take into account that high power levels are required for the fragmentation of the organosilicon precursors [8].

Based on the above mentioned discussion, in the present work we attempt to improve the power coupling in the discharge by investigating the combined effect of the electrode gap and the excitation frequency on the deposition process of SiO_2 thin films from $TEOS/O_2$ discharges. Both these parameters directly affect the plasma impedance [10] so a combination of these can significantly alter the energy transfer from the generator to the plasma. The investigation was carried out by changing the interelectrode space from 12 to 25 mm at two excitation frequencies (13.56 MHz and 27.12 MHz). The real power dissipated in the plasma was recorded by using an accurate technique that includes voltage and current waveform measurement on the powered electrode and is described in the experimental section. At the same time, the variation of the deposition rate with either the electrode gap or the frequency was recorded in-situ by applying Laser Reflectance Interferometry.

2. Experimental procedure

Film deposition studies have been performed in a capacitively coupled high vacuum (HV) parallel plate reactor with a base vacuum of 10^{-7} mbar [11]. The RF power source with matching network is connected to the upper electrode (22 cm in diameter) to sustain the plasma in the chamber. The bottom grounded electrode (19.1 cm in diameter) works as substrate holder and is heated at 373 K. The distance between the two electrodes was varied between 12 and 25 mm. The chamber pressure was kept constant by a downstream throttle valve controller, while the flow rate was independently adjusted using mass flow and liquid flow controllers, respectively. Liquid TEOS is heated up to 70 ^{o}C and together with O_2/He gas mixture were transported to the reactor through a showerhead array of holes in the powered electrode. Silicon (100) wafers were used as deposition substrates. The deposition rate was measured in situ by using Laser Reflectance Interferometry as well as the film thickness, which was 2 μm in all cases.

The RF electrode is powered by a Dressler type Cesar 27.12 MHz generator and an ENI ACG 13.56 MHz, through an L-type matching network. A Prodyn model I-125-2HF current probe and a Hameg AZ91 100:1 attenuating voltage probe are attached to the power lead after the matching network. Voltage and current signals are recorded using a Tektronix 420 digital oscilloscope and then transferred to a computer for Fourier analysis. The method for the measurement of the real power consumed in the discharge at 13.56 MHz has been presented in detail elsewhere [12]. Briefly, in this method an electrical equivalent circuit accounting for the stray impedance of the cell is used in order to convert the current and voltage waveforms, measured outside the chamber to equivalent waveforms at the RF electrode. A shunt circuit is externally connected for increasing the accuracy of the method, while the electrical circuit is complemented to account for power losses in a stray resistance in both the shunt circuit and the cell itself. In the present case, Fast Fourier Transform (FFT) and the counterbalance of cell and shunt resistance are used for increasing phase shift resolution accuracy.

3. Results

The investigation of the interelectrode space effect and frequency on the power dissipation and the power dissipation and the film growth rate was carried out under conditions of constant TEOS partial pressure 0.224 mbar (51 % of TEOS in O_2) and the total gas pressure of 0.4 mbar,. Different sets of electrical measurements have been performed at each frequency and the results of the actual power dissipated in the discharge as a function of the applied voltage are shown in figure 1 and 2. The increase of the applied voltage at 13.56, results to a continuous increase of the power dissipation, which is much more pronounced for the electrode gaps of 20 and 25 mm and applied voltage amplitudes higher than 160 Volt. This behaviour is characteristic of the increase of the power spend by ions, which is expected to be enhanced by the increase of both applied voltage and electrode gap. In addition, the increase of the interelectrode space, for low voltages has almost no effect on the power dissipation but again above 160 Volt there is a clear increase of the power consumption as we go from 15 mm to 20 mm. Further increase of the electrode gap to 25 mm has almost no effect on power.

On the other hand, at 27.12 (figure 2) there is a clear drop of the voltage that is required to operate the discharges at the same or even in a higher power level. The increase of the voltage in this case result to an almost linear enhancement of the power dissipated in the plasma mainly because of the lower applied voltages compared to 13.56 MHz. In addition, at this frequency the increase of the electrode gap for the same applied voltage is not followed by a continuous increase of the power dissipation but to an optimum value located at 15 mm. This optimum indicates that in the case of higher frequencies the power dissipation is much more sensitive in electrode gap variations mainly because of the decrease of the sheath length [10]. The optimum of the energy transfer is achieved at specific ratio of sheaths to bulk lengths, which depend on the total gas pressure and kind of the gas used [13]. At the specific conditions of 0.4 mbar TEOS/O_2 discharges the optimum value appears to be the 15 mm.

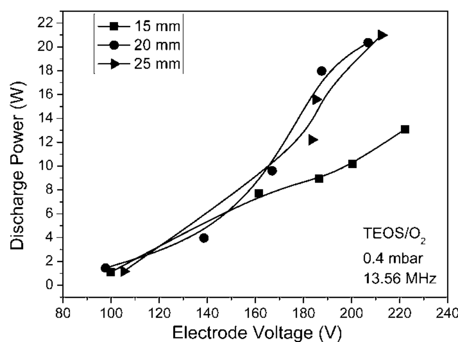

Figure 1. Power dissipated in the discharge as a function of electrode voltage at three different electrode distances at 13.56 MHz

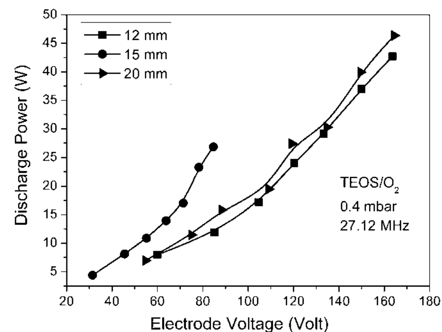

Figure 2. Power dissipated in the discharge as a function of electrode voltage at three different electrode distances at 27.12 MHz

Moreover, if we compare the results of the electrical measurements for the two frequencies, we can clearly observe that at 27.12 there is a significant enhancement of the energy transfer. For instance, if we compare the discharges for the same voltage amplitude (~ 100 Volt) the power dissipation at 27.12 MHz is about 15 Watt, while at 13.56 MHz slightly exceeds 1 Watt. This tremendous difference mainly comes from the discharge current that increases at 27.12 MHz due to the higher plasma density but also due to the increase of number of electron-molecule collisions that enhance the ohmic character of the discharge.

The change of the electrical properties caused by the variation of the electrode gap and frequencies will certainly affect the dissociation process of TEOS in the discharge and in turn the film growth rate. Thus, figure 3 and 4 present the effect of the interelectrode space on the deposition rate of SiO_2 thin films. The increase of the power at both 13.56 and 27.12 MHz leads to an enhancement of the film growth rate although in a different manner depending on the electrode gap. In addition, if we compare the deposition rate for the same power (~ 16 Watt) and the same electrode gap (20 mm) the increase of frequency almost doubles the film growth rate. This result indicates that there is a much more rationalistic consumption of power in the case of 27.12 MHz that finally favours the film growth rate. On the other hand, in the case of 13.56 MHz, the increase of the power that is consumed by ions may limit the dissociation of TEOS in the discharge resulting thus, to the much lower deposition rates.

Another important feature of the deposition rate measurements is that at 27.12 MHz (figure 4) the increase of electrode gap from 15 to 20 mm result to a tremendous increase of the deposition rate by a factor of four, although a better power transfer was measured at 15 mm. This observation clearly indicates that secondary gas phase reactions play a very important role in the deposition process and in fact at these conditions is the main path of production of film precursors. The increase of the electrode gap will favour these reactions in the gas phase as the residence time of all species in the discharge will be increased leading finally to much higher deposition rates. In addition, if we take into account that films with the lower carbon and hydrogen content were deposited at the condition of 27.12 MHz,

electrode gap 20 mm and power 30 Watt, we can express that these reactions are beneficial for the growth of films with highly inorganic character.

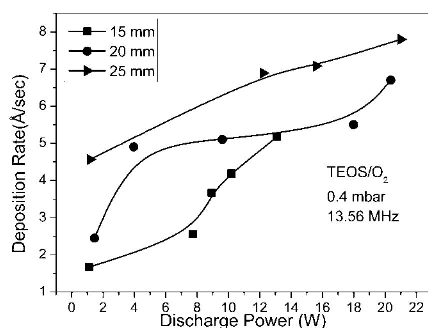

Figure 3. Deposition rate as a function of consumed power at three different electrode distances at 13.56 MHz

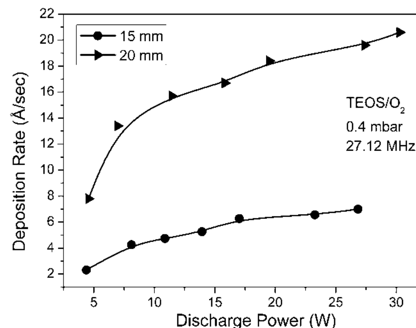

Figure 4. Deposition rate as a function of consumed power at two different electrode distances at 27.12 MHz

4. Conclusions

An investigation of the effect of electrode gap on the electrical properties of different driving frequency (13.56 and 27.12 MHz) TEOS/O_2 discharges and on the growth rate of silicon oxide thin films under conditions of constant TEOS partial pressure was carried out.

The increase of electrode gap was found to monotonically enhance the power dissipation in the discharge at 13.56 MHz, whereas at 27.12 MHz an optimum of power transfer and was observed for the intermediate distance of 15 mm. In addition the increase of frequency was followed by much higher power dissipation although the significant lower applied voltage.

In addition, the increase of electrode gap induces at both frequencies an enhancement of the film growth rate, indicating a significant role of the secondary reactions in the production of film precursors. For the same power level, the deposition rate was almost doubled at 27.12 MHz, due to the much more rationalistic power consumption. Finally, the higher electrode gaps and frequencies was found to lead to films with the lower content of carbon and hydrogen, indicating that this combination is essential for the achievement of rapid growth rates of SiO_2 thin films with a high inorganic character.

5. References

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